

FREQUENCY AGILE MATERIALS FOR ELECTRONICS

workshop proceedings

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***FAME Workshop* Presentation:**

Electric Field Tuning of Microwave Components

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Jeffrey M. Pond

Code 6851

Naval Research Laboratory
Washington, DC 20375

Introduction

Motivations:

- Establish a dialog with Materials Scientists who can provide the microwave community with new/improved materials for tunable applications.
- Explain the microwave community's interest in these materials, how we can use and/or plan to use these materials, as well as our perceptions on potential roadblocks.
- Exchange ideas with others in the microwave community as to how best exploit this emerging technology.



Outline

- Electric field tuning:
 - What electric field tuning does to a microwave device.
 - The advantages and consequences of tuning.
- Material properties and circuit design:
 - Losses — the need for low loss tangents.
 - Consequences of large dielectric constants.
 - Figure of Merit.
 - Thermal stability.
 - Bulk versus thin-film.
- Using tunable dielectrics in microwave components:
 - Discrete capacitors — a ferroelectric varactor.
 - Distributed devices — using tunable transmission lines.
 - + planar transmission lines
 - + waveguides
- The ferroelectric varactor as an example of what is being fabricated and measured
- Conclusions

What Is Electric Field Tuning?

- Electric field tuning is the use of a DC electrical field (bias) to vary some rf property of a microwave device.
- In the most liberal interpretation many conventional microwave devices could be considered to be electric field tuning components. Examples include:
 - PIN diodes.
 - FETs.
 - Varactor diodes.
- In a stricter interpretation, electric field tuning is the application of a tuning voltage which can alter the fundamental characteristics (the phase velocity and/or the characteristic impedance) of the propagation of a guided electromagnetic wave.
 - $v_p = \frac{1}{\sqrt{LC}}$
 - $Z_c = \sqrt{L/C}$

What Is Electric Field Tuning (cont.)?

- The microwave designer would like to be able to use an electric field to control:
 - C , the capacitance per unit length.
 - L , the inductance per unit length.
- Tuning the capacitance per unit length with an electric field:
 - Voltage dependent depletion length in a junction diode.
 - Materials, such as ferroelectrics, which have a field dependent dielectric constant.
- Tuning the inductance per unit length with an electric field:
 - Could piezoelectric properties be coupled to magnetostrictive properties?
 - Would the interaction be so weak as to be useless?

What Are Some Advantages And Disadvantages Of Electric Field Tuning?

- Low power bias supply. There is little or no conduction current in the tunable region. Current flows only when the bias is changed.
- Bias field can often be applied across the same metalization which defines the guided wave structure.
- Bias fields, and hence, bias voltages (\sim kVs), can be large for some geometries/applications.
- In geometries compatible with low bias voltages, rf power levels are small.
- Nonlinearities yield mixing of signals.
- MMIC compatibility.



Material Properties And Circuit Design

- Microwave losses must be low for any material technology to have any practical application.
- Series resistance (outside depletion region) limits semiconductor varactor diode Qs.
- Dielectric loss tangent determines Q ($= 1/(\tan\delta)$) of tunable dielectric materials.
- Conductor losses of guided wave structures will limit overall device Q .
 - ~ 100 to ~ 1000 for thin film planar microwave circuits.
 - ~ 1000 to ~ 10000 for waveguide.
- Goal: Tunable technology should not degrade (or only minimally degrade) the Q of the device compared to a fixed frequency device.

Material Properties And Circuit Design

- The outside world uses 50 Ω characteristic impedance.
- In a transmission line, when a bias dependent dielectric constant is used to tune the phase velocity the characteristic impedance is also varied.
 - Impedance mismatch will limit frequency tunability unless tunable matching sections are used.
 - Tunable lumped element capacitors are the most obvious exception where a very large tunability can be fully exploited.
- The extremely high dielectric constants associated with ferroelectrics can result in difficulty in realizing a 50 Ω characteristic impedance with reasonable geometries.
 - thin film (layered) approaches can be used but aren't microstrip compatible.
 - composite bulk substrates that consist of a ferroelectric mixed with a dielectric.



Comparing Performance of Materials for Devices

- The lower the loss tangent, the better the material.
 - $\tan\delta < 10^{-3}$ yields diminishing/insignificant improvements for planar normal metal devices.
 - $\tan\delta < 10^{-5}$ yields diminishing/insignificant improvements for planar superconducting devices or normal metal waveguide devices.
- The higher the tuning range, the better the material.
 - some applications need a large tuning range.
 - if the entire tuning range isn't needed, then less material can be used and the device Q improved.
- A microwave figure of merit (FM) for such material should be:
 - inversely proportional to the maximum loss tangent over the bias range.
 - proportional to the frequency ratio over which a resonator fabricated on this material could be tuned.

Comparing Performance (cont.)

- Unfortunately, there is no universal Figure of Merit that has been expressed as a simple equation.
 - $FM = \frac{\delta f}{f_0} Q$ can be used if the tuning range is small.
 - Caution must be employed when trying to compare two materials; one with relatively low Q and high tuning range, and the other with relatively high Q and low tuning range.
- Until an appropriate expression can be derived, it is necessary to consider the particular application envisioned and compare materials with similar tuning ranges and/or Q s. In those cases, the expression above is useful.



Thermal Issues

- Ferroelectrics possess an inherent temperature dependence in their dielectric properties.
- Microwave devices and circuits are expected to operate in a temperature independent fashion over a significant ambient temperature range.
- Self heating due to absorption of microwave power must be considered especially with low Q materials and/or high rf powers.
- Temperature sensitivity is an issue that must be addressed:
 - provide a controlled thermal environment — heater and/or cooler
 - temperature compensation included in the microwave design
 - cryogenic operation such as required for HTS components could provide a very stable environment at "no extra cost"

Comparing Bulk and Thin-Film Ferroelectrics

Relative Advantages and Disadvantages

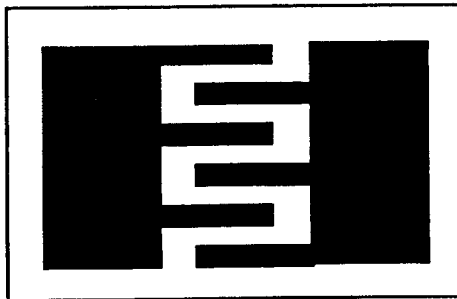
	Bulk (single x-tal & ceramic)	Deposited thin films
Power Handling	+	—
Microstrip Compatible	+	—
Low Bias Voltages	—	+
MMIC Compatible	—	+
Variety of Characteristics	—	+
Expense	—	+
Compatible ϵ_r	+	—
Microwave CAD tools	+	—



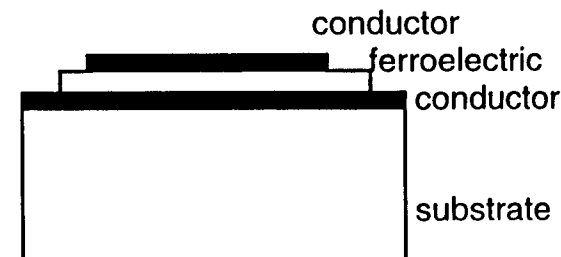
Using the Tunable Dielectric Material

- Discrete tunable capacitors.
 - interdigitated.
 - + bulk substrate.
 - + thin film.
 - parallel plate.
 - + thin film.
 - + thinned substrate technology.
 - useful capacitances for most microwave application are from 0.1 pF to 10 pF.

Interdigitated Capacitor Top View



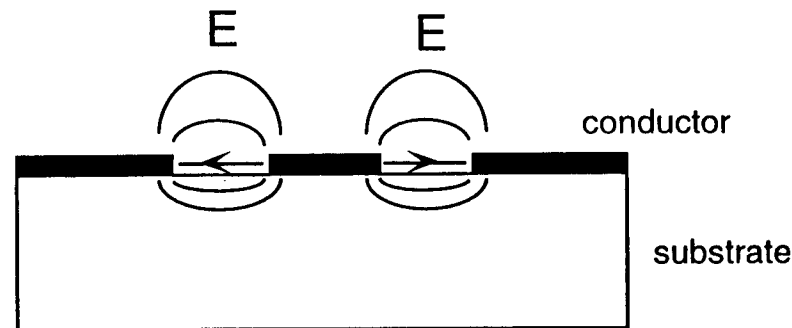
Parallel Plate Capacitor Side View



Using the Tunable Dielectric Material (cont.)

- Candidate planar transmission lines (cont.):
 - coplanar waveguide, coplanar stripline, and coplanar slotline:
 - + all conductors on top side of substrate.
 - + field orientation is appropriate for thin-film or bulk ferroelectrics.
 - + small gaps between electrodes can be used resulting in lower bias voltages, but at the expense of increased metal losses.

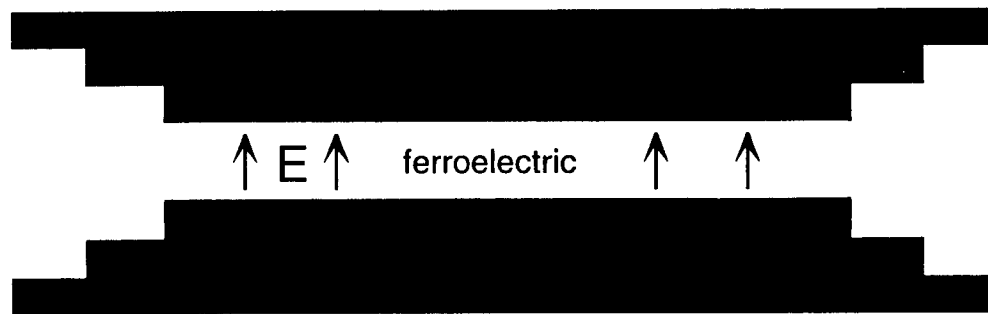
Coplanar Waveguide Cross-Section



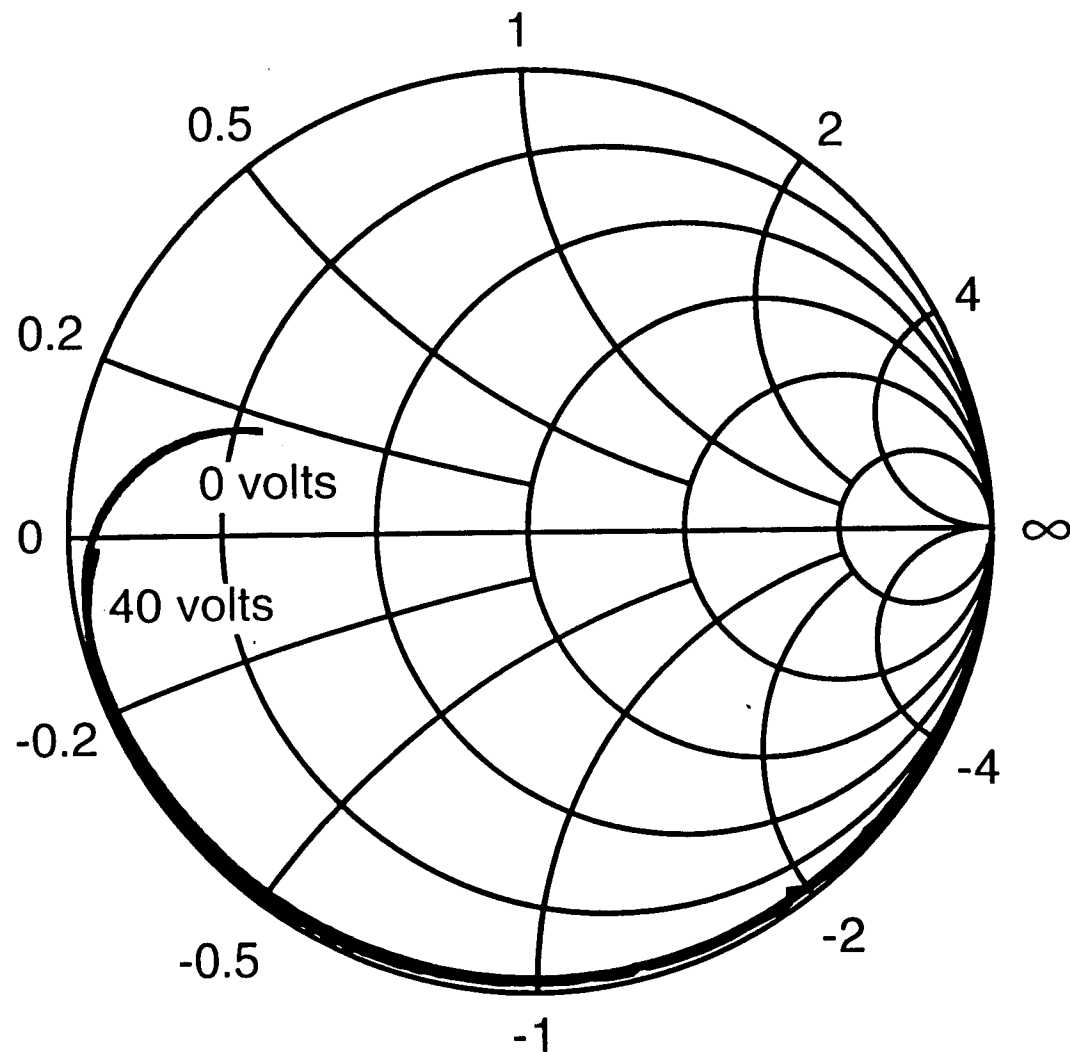
Using the Tunable Dielectric Material (cont.)

- Candidate waveguide:
 - rectangular waveguide:
 - + large bias voltages compared to planar transmission lines.
 - + high power handling capability.
 - + unless losses are kept low heat dissipation can be an issue.

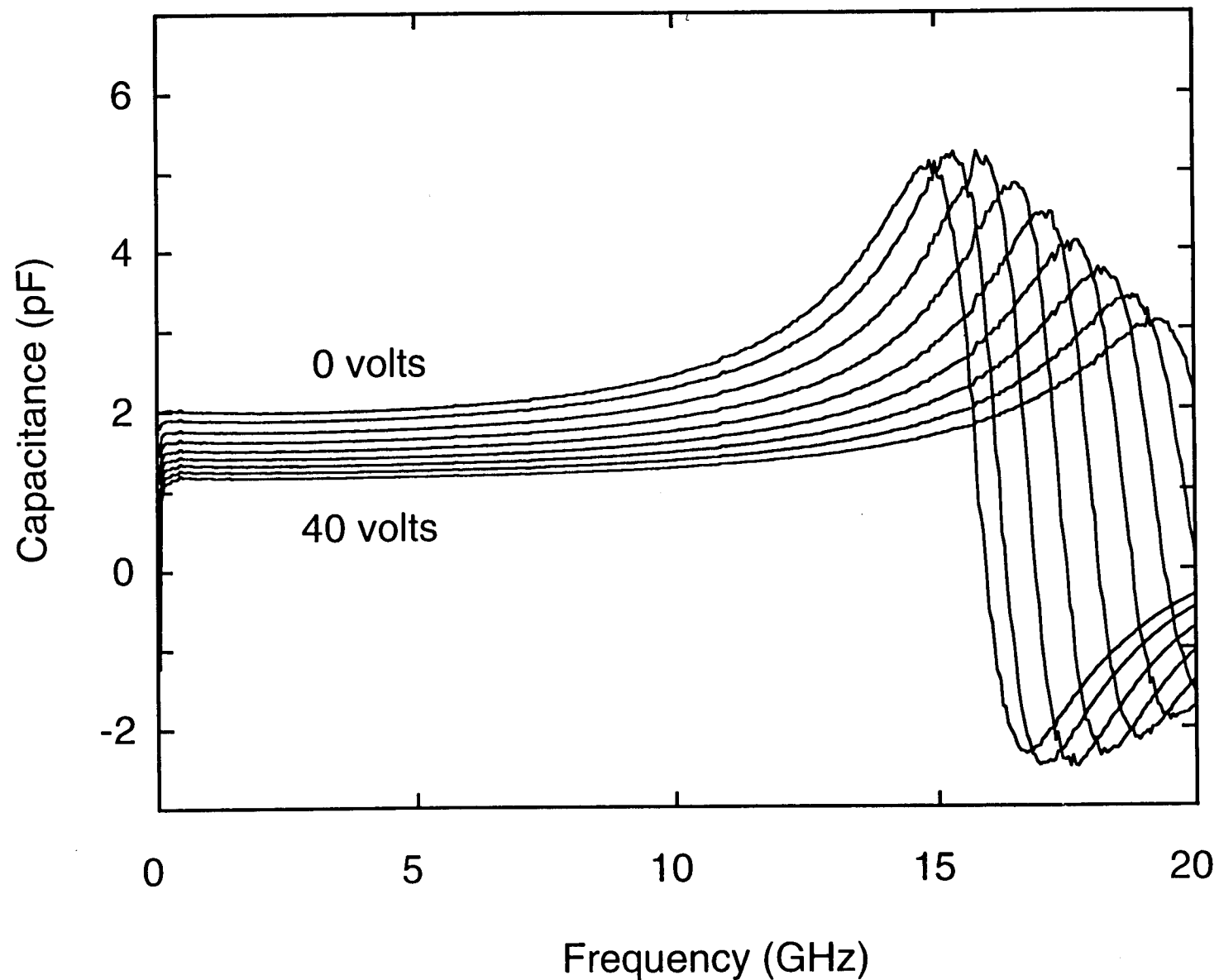
Waveguide Phase Shifter



**Ag Electrode Interdigitated Capacitor on
600 nm-thick $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$ on MgO**



Ag Electrode Interdigitated Capacitor on 600 nm-thick $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$ on MgO



Conclusions

- There are a lot of applications for low loss electrically tunable microwave components.
- Significant progress has been made in developing both thin film and bulk tunable dielectrics but the losses are still too high for many applications.
- Combining electric field tuning and magnetic field tuning so that phase velocity and characteristic impedance can be independently controlled would provide the ultimate in design flexibility.
- Lowering the loss should be a/the major goal.